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Consumption Change-Induced Transients in a Water Distribution Network: Laboratory Tests in a Looped System

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Key Points:

- Several laboratory transient tests are carried out in a polymeric looped water distribution network (WDN) due to deterministic and stochastic consumption variations
- The results may help the water utilities to identify the reasons for the high occurrence and severity of faults in some portions of WDNs
- The reasons for faults may be repetitive and fast consumption changes, especially at night, and a high small-diameter pipe percentage

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Abstract At the Water Engineering Laboratory of the University of Perugia, Italy, a wide experimental program has been carried out in a polymeric pipe network with two 100 × 100 m square loops. The aim of this program is to analyze the dynamic response of the system to transients caused by a change in water consumption. To emphasize such a response, transients are generated by the complete and fast closure of an end-user, located at the downstream end of a service line. During tests, the combined effect of simultaneous consumers, whose consumption is varied both deterministically and stochastically, has been analyzed. The tests allow examining the propagation of the generated pressure waves within the network for different water consumption variations and end-user locations. The lessons learnt from the experimental results may help the water utility managers to identify the reasons for the higher frequency of occurrence and severity of faults in some specific portions of water distribution networks apparently "similar" to others where damages are less frequent and severe.

1. Introduction

In pipe networks, the pressure plays a key role and, in particular, pressure variations due to transients can induce additional stresses not only on pipes, but also on the other components, such as junctions and devices.

Traditionally, in transmission mains attention is focused on the effects of a valve maneuver, carried out to set an appropriate discharge, or pump trip that can give rise to severe overpressures (Liou & Wylie, 2016; Meniconi et al., 2018; Meniconi, Capponi, et al., 2021). Very different is the approach with respect to transients in water distribution networks (WDNs) which are the topic of this paper. Precisely, the effects of the transients in WDNs are often underestimated in the belief that such systems are always intrinsically self-protected against them. Such a conviction is based on the assumption that a large part of the generated pressure waves would exit through the consumers that, when active, behave as pressure relief valves. Thus, pipe breaks in WDNs are attributed to the large mean pressure or, in case the pressure regime is considered as appropriate, the inaccurate installation of pipes, additional loads due to traffic, and the large number of connections that undermine the integrity of the system. As a remedy against the large pressure regime and leakage, in WDNs the installation of pressure reducing valves (PRVs) is a common practice (e.g., Meniconi et al., 2017).

Posed the question in these terms, in many cases it is arduous identifying the actual cause of the large leakage that characterizes only some parts of a WDN that exhibit no clear differences with respect to other ones in terms of pipe material, maintenance, external loads, as well as the pressure values, usually monitored at a low frequency. A possible explanation of such a feature could derive from a proper identification of the nature of the actually dangerous transients and the different exposure to them of individual parts of the considered WDN. With the aim of explaining the results achieved by this paper and pointing out the open questions and urgent matter to address, a literature review is offered below.

Numerous papers analyze numerically the transient behavior of a WDN. More in details, the numerical papers deal with four main aspects: (a) the use of transients for detecting an anomaly (Che et al., 2022; Haghighi & Ramos, 2012; Misiunas et al., 2006; Shi et al., 2020; Vítkovskỳ et al., 2000, 2003) or treating biofilm (Zeidan & Ostfeld, 2022), (b) the performance of different numerical models (Axworthy & Karney, 1997, 2000; Creaco et al., 2017; Filion & Karney, 2002; Nault & Karney, 2016; Nault et al., 2018; Pal et al., 2021; Ulanicki & Beaujean, 2021; Vítkovskỳ et al., 2011; Wood et al., 2005; Zecchin et al., 2014) with particular regard to the effect of the layout simplification—skeletonization—(Huang et al., 2017; Huang, Zheng, Duan, Zhang, & Shen, 2020;

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Jung et al., 2007; Meniconi, Cifrodelli, et al., 2021) and uncertainties in the pipe properties and actual state of the system (Edwards & Collins, 2014; Kazemi & Collins, 2018a, 2018b), (c) the effect of boundaries and control devices (Jung & Karney, 2006; Karney & McInnis, 1992), and (d) the identification of the most severe scenarios in terms of pressure variations: for example, water consumption fluctuations (Haghighi, 2015), pump trip (Huang, Zheng, Duan, & Zhang, 2020) or transients generated in the supply line (Bohorquez et al., 2020) for a real-time control (Creaco et al., 2019; Prescott & Ulanicki, 2008), by evaluating the optimal sensor location for capturing fast pressure variations (Zecchin et al., 2022).

On the contrary, very few papers deal with transient laboratory and field tests. With regard to the former, the most active research group is the one at the University of Adelaide, Australia. However, the overwhelming part of such experiments concern a single, quite short (with a length of about 40 m), and small diameter (about 20 mm) copper pipe. Such a circumstance makes these papers out of topic for the analysis provided in this paper. The only exception is the paper by Zeng et al. (2021) in which the mentioned copper pipe—with two artificial leaks—is connected to the Adelaide water main through a polymer hose and a copper pipe at each side for anomaly detection. However, the transients carried out in the real WDN are not of interest for the present analysis as they fall within what the Authors call "background noise", a feature that must be reduced to better localize the leaks. A further contribution is offered by the research group at the University of Sheffield, UK, in the conference paper by Hampson et al. (2014), where the transient source location has been detected in a 25 mm MDPE pipe network with a single 20 × 20 m square loop and two branches by comparing the experimental arrival time of transient pressure primary wave fronts and those estimated by the graph theory.

The literature is slightly more extensive for field tests. Specifically, the usefulness of acquiring the pressure signals at a low frequency (15 min) or higher frequencies is discussed in Mounce et al. (2012), Machell et al. (2014), and Mounce et al. (2015). Furthermore, an example of the application of the transient test-based techniques for a leak survey in a WDN is offered in Meniconi et al. (2015), where transients are generated by a pump trip. In addition, Stephens et al. (2011) check the performance of unsteady models for transients generated by the closure of a small valve, installed at two separate locations, with pressure measured only at three sections. The considered system is a small-town WDN—with two loops and several branches supplied by a tank—comprising 4 km of pipe of homogeneous material (asbestos cement, with a diameter ranging from 96 to 231 mm). However, also these tests are of limited relevance in the light of the present paper: transient tests are carried out during the night, just to reduce the impact of water consumption (see below). The analysis of two transient tests carried out in a real WDN with three loops of pipes of different material and diameter (cast iron pipes with a diameter from DN80 to DN250, and PVC pipes with a diameter from DN100 to DN200) is reported in Gong et al. (2018) to verify the damping effect of a plastic pipe replacing an old metallic one in a relay program. The transients are generated by the opening and closing of a solenoid valve installed in the plastic pipe, and then characterized by a lower impedance with respect to the other WDN pipes, and pressure is measured only in four measurement sections at the main pipes. In the conference papers by Starczewska et al. (2014), Starczewska, Boxall, and Collins (2015), and Starczewska, Collins, and Boxall (2015), the transient behavior of WDNs is analyzed. Specifically, in Starczewska et al. (2014) transient tests, due to pump trip, show no decrease in the transient upsurges amplitude despite progression from trunk to distribution pipes. The Authors notice that the pressure waves do not damp because of the presence of several contractions and dead ends. In Starczewska, Boxall, and Collins (2015) tests are carried out in two areas of a WDN dominated by industrial user and pump activity, respectively. The data are used to demonstrate the validity of a methodology that quantifies the pressure changes experienced by pipes and evaluate the fingerprint in terms of pressure gradient. In Starczewska, Collins, and Boxall (2015), a high frequency pressure monitoring is carried out for two weeks in two sections of five differently supplied sites of WDNs. These have been chosen to represent the complexity of the water network with looped and branched connections included. The aim is to correlate the severity of transients to pipe material, diameter, age, WDNs complexity, and types of users. A conclusive result has not been achieved, with only the percentage of plastic pipes, and the source of the transient (e.g., pumps, commercial users) proven to be significant. The Authors highlight the need to better understand the widespread occurrence of transients within complex WDNs. Such a conclusion reinforces what explicitly pointed out in the pioneering paper by McInnis and Karney (1995), where the results of a single field test are reported. Precisely, it is stated that "the results are not sufficient to generalize about the transient behavior of pipe networks. On the contrary, experience gained from this field test indicates that more rigorous field-testing programs are necessary if we are to isolate and understand the nature of transient flow in complex pipe systems." In fact, in most cases, in real WDNs, very few tests (or just a single test) are carried out for several reasons, with the main being the evident non-repeatability of the tests. This circumstance makes very hard to generalize the obtained results. In complex systems, as WDNs, the cause-and-effect link is not clear: a given measured overpressure could be due to several causes also because several are the possible paths of the pressure waves. More successful is the correlation between the varying pressure and the main failure highlighted in Rezaei et al. (2015) for data acquired in 48 District Metered Areas (DMAs) feeding a total population of approximately 100,000 people in UK.

From the above literature review it emerges that in the few available papers based on physical experiments, transients are generated by maneuvers in the supply lines (e.g., pump trip), and their effects are analyzed in the main pipes. Such a phenomenon is very different with respect to the transients generated within the network (i.e., in the service lines) due to water consumption variations. Indeed, such transients are very frequent, one could say "almost continuous", and very few papers analyze in details their effects experimentally (Lee, 2015; Lee et al., 2012; Marsili et al., 2021, 2022). As a premise to properly analyze the characteristics of transients in WDNs, it is important to make a distinction between the main pipes and service lines, that usually meet at a junction. The former are the municipal pipes and form the distribution network, whereas the latter connect the main pipes to the internal plumbing systems of individual users. Such a distinction is motivated in two respects. The first respect is of an administrative nature: the municipal pipes and service lines (up to the curb stop or water meter) are maintained by the utility company, whereas the remaining part of the service lines is under the user's responsibility. The second respect concerns the characteristics of these two components, with the diameter of the main pipes being significantly larger than the one of the service lines. In Marsili et al. (2021, 2022), the pressure signals acquired in a real WDN in ordinary operational conditions (i.e., with no maneuvers on pumps or valves in the main pipes) indicate that the short term pressure variations occurring in the main pipes are due to the water consumption changes. In Lee et al. (2012), laboratory experiments concern a limited (i.e., six) number of tests on a tree layout system. Transients from both outside (i.e., generated in the main pipe), and inside (i.e., within the plumbing system) are considered. The main goal of these tests is to point out the possible occurrence of negative pressures, and related back-flow phenomena, in the plumbing system. Accordingly, pressure traces are not acquired in the main pipes. In Lee (2015), the main aims are to check whether transients generated in the main pipes are responsible for the failure in the service lines and a leak in the service line may attenuate pressure waves. However, the few carried out tests do not allow drawing general conclusions and highlighting the role of the location of the transient source, as well as of the entity and the simultaneity of water consumption changes, for a given layout.

To fill this gap, this paper focuses on the experimental analysis of the effects of transients due to changes in the users' water consumption, that are surely the most frequent source of pressure variations in a WDN. The motivation is that, for the intrinsic characteristics of WDNs, only laboratory tests allow isolating and understanding the nature of the transients. In fact, in real systems, since boundary conditions change in an uncontrolled way, repeatability of tests is a very hard task to achieve and then it is quite arduous to examine in details the effect of each cause of transients.

The main aim of the carried out laboratory tests is to investigate whether changes in the users' consumption in the service lines may generate dangerous pressure variations also in the main pipes. In this concern, the entity of these variations and their frequency of occurrence are analyzed from two different points of view: on the water utility and user side (Loganathan & Lee, 2005). Accordingly, in the present paper, the transient behavior of a looped WDN (two 100 × 100 m square loops)—with one or more active service lines in different locations—is analyzed via experiments conducted in the Water Engineering Laboratory (WEL) at the University of Perugia, Italy. During tests, pressure signals are acquired both in the main pipes and service line, where the downstream end valve simulates an end-user located downstream of the water meter. Transients are generated by the fast and total closure of such a valve simulating the effect of rapid maneuvers of an end-user.

The organization of this paper is as follows. Section 2 includes a description of the experimental set-up, a brief breakdown of the laboratory transient tests, and it introduces the key quantities that characterize the network transient response. The possible occurrence of cavitation in the service line and the acquired pressure signals for no-cavitating flows are shown in Sections 3 and 4, respectively. Section 5 focuses on the effect of the end-user discharge variations during the first phases of the transients and along time. The combined effect of simultaneous consumers—with consumption varied both deterministically and stochastically—is highlighted in Section 6. Finally, conclusions are drawn in Section 7.

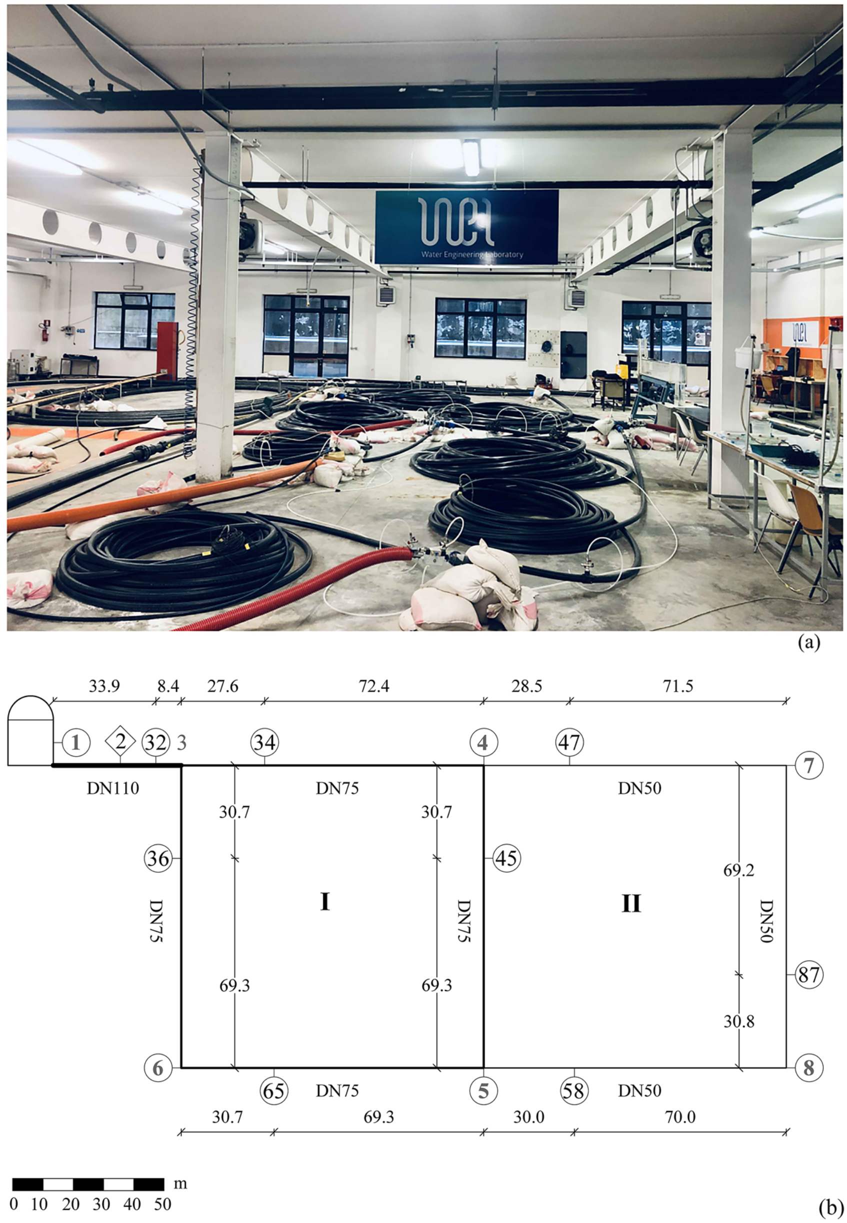


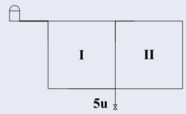
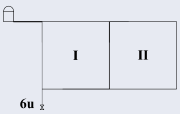
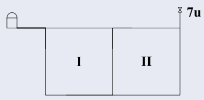
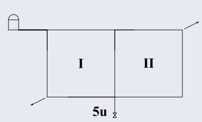
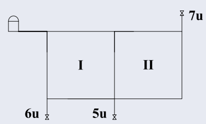
Figure 1. The two-loop network at the Water Engineering Laboratory of the University of Perugia, Italy: (a) picture and (b) layout with the pipe length and location of the measurement sections indicated.

2. Materials and Methods

2.1. The Experimental Set-Up

The experimental set-up at the WEL of the University of Perugia, Italy is a pipe network with two loops simulating a DMA. All the pipes are high density polyethylene pipes and are supplied by a pressurized tank (Figure 1a) in which the head is assured by a pump. The two loops of the DMA are supplied by a 42.3 m long pipe with an internal diameter, D, equal to 93.3 mm, nominal diameter DN110, and wall thickness e = 8.1 mm. Loop I has four 100 m long pipes with D = 63.8 mm, DN75, and e = 5.6 mm, whereas loop II has four pipes one in common with the first loop and the other three ones with D = 42.6 mm, DN50, e = 3.7 mm, and a length of 100 m (Figure 1b). In order to simulate a service line, a DN25 branch (D = 20 mm and e = 3 mm) with a length of 23.6 m has been alternatively or simultaneously installed at Sections 5–7 (Table 1).

Table 1
Main Characteristics of Some of the Tests Carried Out at Water Engineering Laboratory

Test series (#)	Layout	Other open sections	Discharge $[10^{-3}\ \mathrm{m^3/s}]$
1 (closure at 5u)		-	$Q_{0,5u}=0.04$ $Q_{0,5u}=0.1$ $Q_{0,5u}=0.2$ $Q_{0,5u}=0.4$ $Q_{0,5u}=0.7$ $Q_{0,5u}=0.9$
2 (closure at 6u)		-	$Q_{0,6u}=0.04$ $Q_{0,6u}=0.1$ $Q_{0,6u}=0.2$ $Q_{0,6u}=0.4$ $Q_{0,5u}=0.7$ $Q_{0,5u}=0.9$
3 (closure at 7u)		-	$Q_{0,7u}=0.04$ $Q_{0,7u}=0.1$ $Q_{0,7u}=0.2$ $Q_{0,7u}=0.4$ $Q_{0,7u}=0.6$ $Q_{0,7u}=0.9$ $Q_{0,7u}=1.1$
4 (closure at 5u)		6	$Q_{0,5u}=0.4$ $Q_{0,6}=0.3$
		7	$Q_{0,5u}=0.4$ $Q_{0,7}=0.3$
		6, 7	$Q_{0,5u}=0.4$ $Q_{0,6}=0.3$ $Q_{0,7}=0.3$
5 (random opening and closure at 5u, 6u, and 7u)		variable	variable

To determine the unsteady-state behavior of the network, the pressure wave speed, a, has been experimentally evaluated by measuring the travel time of the pressure waves. The so-obtained values are: a_{DN25} = 455.91, a_{DN50} = 379.81, a_{DN75} = 387.89, and a_{DN110} = 398.82 m/s, with the subscripts indicating the corresponding pipe nominal diameters. Such values are compatible with the geometrical and mechanical characteristics of the pipes.

To simulate the end-user, at the downstream end of the service line (i.e., at nodes 5u, 6u, and 7u—Table 1) a solenoid valve in series with a ball valve is installed. The ball valve—equipped with a protractor to check the actual opening degree—allows simulating different water consumption, whereas the solenoid valve generates controlled, repeatable, and fast transients. It is worthy of noting that fast transients imply sharp pressure waves. Such a requirement for pressure waves is of great importance not only when they are used for fault detection (Brunone et al., 2021) but also for understanding the mechanisms of interaction with the system component as in this paper.

For evaluating the end-user hydraulic characteristics, the flow-rate curve of the in-series valves, described by Equation 1, has been obtained by steady-state tests:

$$A_E(\phi) = \frac{Q}{\sqrt{2g\zeta(\phi)}} \tag{1}$$

in which A_E ($\mathrm{m^2}$) = valve effective area, Q ($\mathrm{m^3/s}$) = discharge; ϕ = dimensionless relative opening, ζ (m) = local head loss across the in-series valves, and g = gravity acceleration (= 9.806 $\mathrm{m/s^2}$). Based on the experimental results, the following fitting function has been derived: $A_E(\phi) = 0.00025\phi^2 - 0.00001\phi$.

In all the considered layouts of the system, the supplied steady-state discharge is measured at section 2, located at a distance of 22.2 m from the tank, by means of an electromagnetic flow meter (Figure 1b). Pressure is monitored at nodes 1, 4, 5, 6, 7, and 8, as well as at the measurement sections denoted with two numbers indicating the closest and the farthest junction, respectively (Figure 1b). As an example, the measurement section 32 is located at a distance of 8.4 m from node 3, whereas it is farther (=11.7 m) from node 2. To capture properly the features of the system transient response, during tests, pressure is sampled at a frequency of 2,048 Hz by a National Instrument cDAQ-9188 data acquisition system with a maximum analog input single-channel sampling rate of 51.2 kilosamples per second. Absolute (A) and relative (G) piezoresistive pressure transducers have been installed with a full scale (*fs*) variable from 6 bar G to 10 bar G within the network and from 15 bar A to 16 bar A in the service line; such transducers have an accuracy of 0.25% *fs*.

It is worth noting that the experimental set-up has been designed in order to be representative of real WDNs, on the one side, and allow an effective analysis and comprehension of the phenomena, on the other side. Indeed, it has to be pointed out that: (a) the loops of the experimental set-up consist of pipes of different diameters, thus allowing a proper analysis of the effects of the pipe size on the system response to the user water consumption change, (b) the water consumption change can be physically modeled in parts of the system with different characteristics such as at connection of three pipes of different diameters, large and small diameters (see node 5) or at the connection of a couple of pipes with the same diameter (both large or small, such as node 6 and 7, respectively), and (c) given its topological structure, the system allows taking into account transmission and reflection of the pressure waves at nodes featuring different geometrical characteristics (number of the connected pipes, ratio of the diameters of the pipes), as in real systems. Furthermore, pipe lengths and diameters as well as the types of connection considered in this system are quite common and indeed the system is conceived taking cue from a part of the real WDN considered in the field analysis by Marsili et al. (2021).

2.2. Laboratory Transient Tests

Table 1 shows the main characteristics of some of the tests carried out at WEL. Such tests differ for the layout, boundary conditions, and initial discharge of the end-user, $Q_{0,yu}$, with subscripts 0 and *yu* indicating the steady-state conditions and the end-user (with $y = 5$, 6, and 7, alternately), respectively. For a given relative opening of the end-user, ϕ, the discharge $Q_{0,yu}$ has been obtained by Equation 1. To simulate actions initiated in the plumbing system—that is, the shutting off the valve, shower heads or the automatic off of the solenoid valve on the washing machine—transients are generated by the complete closure of the end valve. Such a maneuver emphasizes the dynamic response of the system, and the variation of the discharge, ΔQ_{yu}, generating the overpressure Δ_{yu}, coincides to $Q_{0,yu}$. In particular, tests with $Q_{0,yu}$ smaller than about 0.4×10^{-3} m^3/s are consistent with the typical consumption of sanitary appliances (Blokker et al., 2010). On the contrary, tests with larger values of $Q_{0,yu}$ refer to more important users (e.g., of industrial or commercial type).

During test series #1, #2, and #3, only one end-user is active (precisely: node 5u, 6u, and 7u, respectively). The aim of these tests is to analyze the effect of the discharge variation, when the generated pressure waves propagate in a completely closed network. On the contrary, during test series #4, several users are still active (precisely: nodes 6 or/and 7), after the completion of the maneuver at the end-user 5u. This series allows examining the effect of the WDN functioning conditions (i.e., the pressure regime and the values of the discharge in the pipes).

Finally, in order to consider realistic and randomly varying water consumption patterns at different nodes of the system, a test featuring 1 hr of random water consumption variations in all the three end-users (i.e., nodes 5u, 6u, and 7u), for more than one hundred and fifty opening and closing maneuvers, is performed (test series #5). The water consumption pattern simulated in each node is definitively representative of the operations of users in pipe networks since it has been obtained by field monitoring of real users (Marsili et al., 2021, 2022).

2.3. Key Quantities Characterizing the Network Transient Response

To compare different transient tests, the dimensionless pressure signal is considered:

$$h = \frac{H - H_e}{\Delta_u} \tag{2}$$

where H (m) is the pressure head, the subscript e indicates the end conditions achieved when the effect of the maneuver fully vanishes, and Δ_u (m) denotes the pressure head variation generated by the maneuver at a given end-user. In Equation 2, pressure head is referred to H_e since this value is more representative of the dynamics of

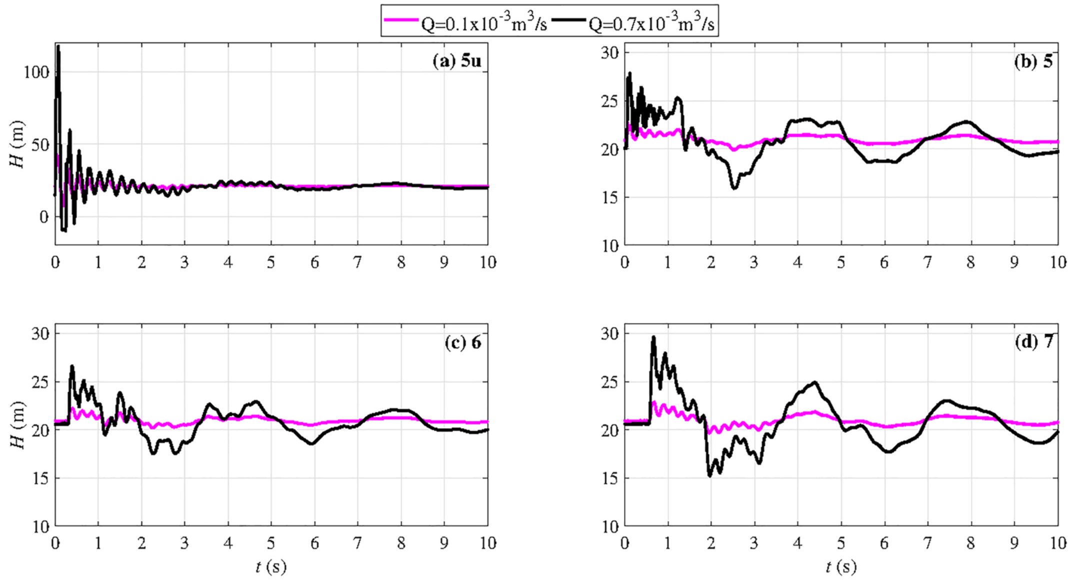


Figure 2. Test series #1—pressure signals for $Q_{0,5u} = 0.1$ and 0.7×10^{-3} m^3/s acquired at nodes: (a) 5u, (b) 5, (c) 6, and (d) 7.

the transient event. In fact, after the completion of the maneuver, pressure oscillates around H_e which represents the end state, or the new steady-state, of the system, that can be also very far from the pre-transient conditions. Moreover, in order to capture the propagation of Δ_u in the network, the dimensionless first pressure variation, δ, is evaluated as:

$$\delta = \frac{\Delta}{\Delta_u} \tag{3}$$

with Δ = first pressure variation at a given measurement section. Finally, to point out the most stressed part of the network, not only during the first characteristics time but along time, the instantaneous hoop stress, given by the classical Mariotte-Barlow formula $\left(= \frac{H D\gamma}{2e}\right)$ is considered, with γ = liquid specific weight. More precisely, to take into account the whole time-history of the pressure variations, $|H - H_e|$, to which is subjected each measurement section, the cumulative value of the hoop stress, σ, is calculated as:

$$\sigma = \sum_t \frac{|H - H_e|\, D\gamma}{2e} \tag{4}$$

with t = time elapsed since the beginning of the maneuver.

3. Occurrence of Cavitation in the Service Line

As an example of the generated transients, Figure 2 shows the pressure signals (i.e., the time-history of the pressure head), H, acquired during test series #1, with $Q_{0,5u} = 0.1$ and 0.7×10^{-3} m^3/s at four sections, considered as exemplary: the downstream end section of the service line (Figure 2a), junction 5 (Figure 2b), the connections in series 6 and 7, in the first (Figure 2c) and second loop (Figure 2d), respectively. It is worthy pointing out that in all figures of sections 3 and 4, each line refers to a different flow-rate at the end-user.

As highlighted in Figure 2a, for both the discharges most of the incident pressure wave is reflected back by junction 5 with a negative sign. Then it doubles at the now closed user, whereas very small amplitude wave propagate into the network (Figures 2b–2d). Specifically, for the largest value of the discharge, the pressure ranges between −10.33 and 118 m in the service line, and between 15 and 30 m in the network. In other words, according to Lee et al. (2012), Figure 2a confirms the risk of the occurrence of the water column separation in the service line, but not in the main pipes. This implies that for $Q_{0,5u} = 0.7 \times 10^{-3}$ m^3/s (with cavitation), the pressure signal at the measurement section 5u exhibits a quite different dynamics (Cannizzaro & Pezzinga, 2005) with respect to

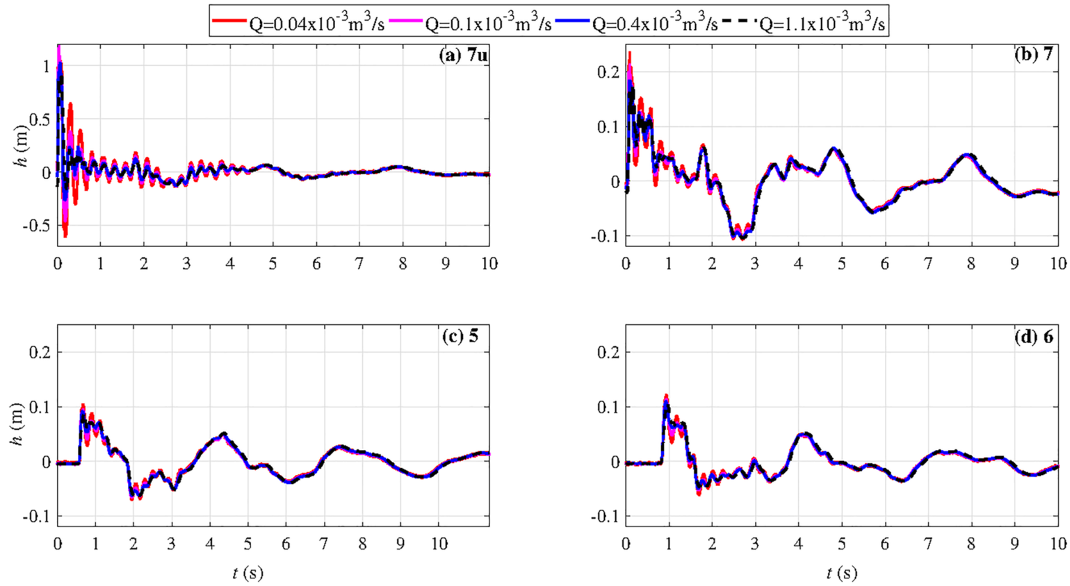


Figure 3. Test series #3—dimensionless pressure signals for $Q_{0,7u} = 0.04, 0.1, 0.4, 1.1 \times 10^{-3}$ m^3/s acquired at nodes: (a) 7u, (b) 7, (c) 5, and (d) 6.

the test for $Q_{0,5u} = 0.1 \times 10^{-3}$ m^3/s (without cavitation). The depressurization generated by large users can pose severe problems in the service line: not only the generation of vapor bubbles or water column separation, as for $Q_{0,5u} = 0.7 \times 10^{-3}$ m^3/s, but also the possible intrusion of contaminants (e.g., Collins et al., 2012).

4. Pressure Signals for No-Cavitating Flows

To analyze a larger range of no-cavitating flows, the pressure signals acquired during test series #3 are taken into account (Figure 3). Specifically, Figure 3a confirms that, also at the end-user 7u, the pressure variation generated by the maneuver gets trapped into the service line. In fact, this branch is overexcited since most of the pressure wave incident at junction 7 is reflected back. However, it does not achieve cavitating conditions, even for higher consumption variations, as it happens for test series #1. This difference is mainly due to the fact that node 7 is a multiway junction connecting three pipes instead of four, as for junction 5. Consequently, the transmitted waves toward the network are larger—since the energy is diverted into less paths—and the reflected one toward the service line is smaller. Indeed, the transmitted pressure waves are about 23% and 10% of the incident pressure wave for test series #3 and #1, respectively, whereas the reflected one is 77% and 90%. However, as it will be discussed below, for both the layouts, the most stressed part of the network is the one at nodes 7 (reported in Figure 3b) and 8 (not shown for the sake of shortness). Such a result is corroborated by an in depth analysis carried out both in the short and long terms with regard to the dimensionless first pressure variation, δ, and the cumulative hoop stress, σ, respectively, that will be discussed in the next sections.

5. Effect of the End-User Discharge Change

5.1. Transient Response of the Network During the First Phases

In order to explain more clearly the mechanism of propagation inside the network of the pressure wave generated by maneuvers at the end-user, in Figure 4, the behavior of δ at most of the measurement sections in the network is shown. First, for a given measurement section, a clear dependence of δ on the consumption has not been observed. This confirms the fact that during the first phase of the transients the topology of the network prevails on the system hydrodynamics. Second, for a given test series, the most excited section is node 7. This result does not surprise for test series #3 where the maneuver is carried out at 7u: node 7 is the first node reached by Δ_u (Figure 4f). For test series #1, and #2, such a feature can be ascribed to the particular topology of the system (uniform material and length of the loop pipes). As highlighted in Figures 4d and 4e, this is due to the almost simultaneous arrival of different pressure waves at node 7. Third, a global analysis of the three test series

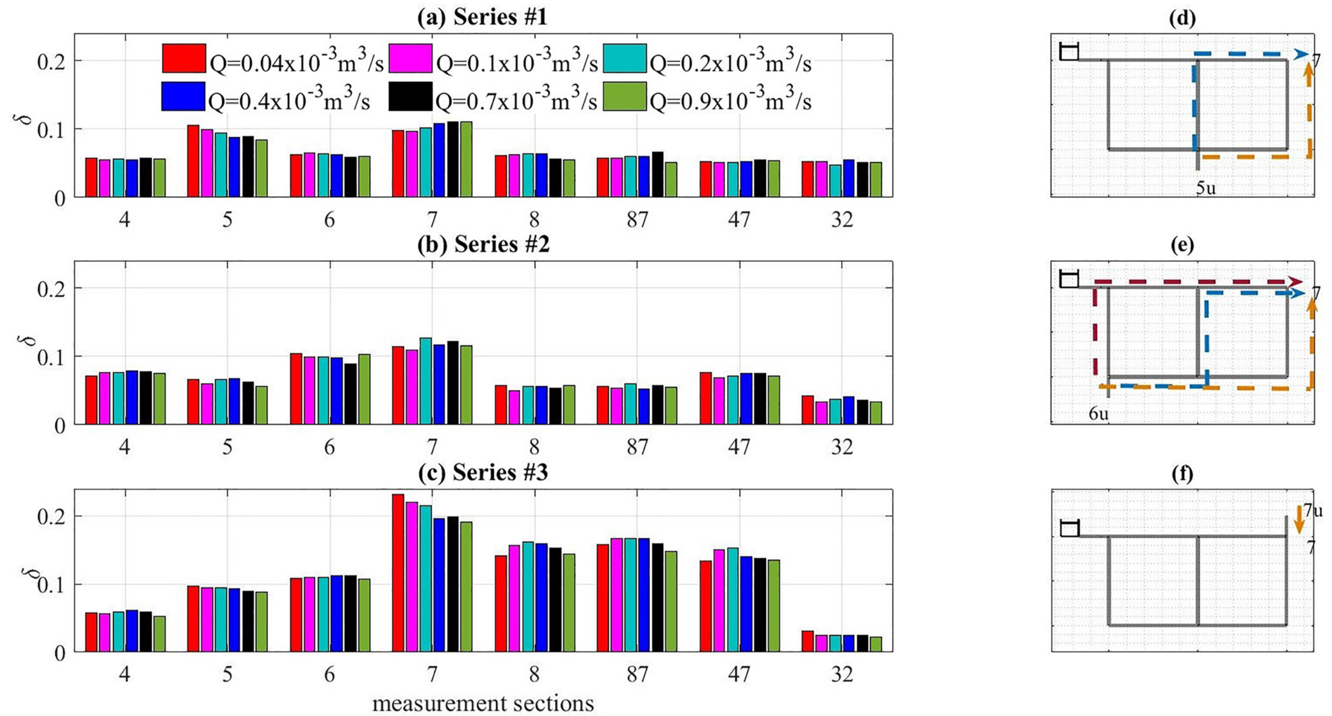


Figure 4. The dimensionless first pressure variation at the measurement sections, δ, for different $Q_{0,yu}$ and the propagation of the pressure wave generated by the maneuver toward node 7 for: (a and d) test series #1, (b and e) test series #2, and (c and f) test series #3.

in the short term suggests that the most excited scenario is the one where the maneuver is carried out at node 7u. On the one hand, comparing series #1 and #3, this is due to the already mentioned simpler shape of junction 7 with respect to junction 5: a larger amplitude pressure wave does enter into the network. On the other hand, this remark cannot explain the different behavior of test series #2 and #3, since junctions 6 and 7 have the same shape. However, it is worthy pointing out the crucial role of the ratio between the main pipe cross-sectional areas connected to the service line, and the service line itself, for a given pipe material: the smaller this ratio—that is, the higher the pipe impedance ratio—the larger the transmitted pressure wave (Bohorquez et al., 2020; Swaffield & Boldy, 1993). This is the reason why series #3 experiences the largest range of the no-cavitating flow in the service line.

5.2. Transient Response Along Time

To better emphasize the effect of the discharge along time, the cumulative hoop stress given by Equation 4 is evaluated for pressure signals of Figure 3 and reported in Figure 5. As expected, the larger $Q_{0,7u}$, the larger the stress. It is worth pointing out that nodes 5 (Figure 5c) and 4 (not shown for the sake of shortness) are quite similar in terms of stress. However, the closer the node to the tank, the smaller the stress (see, e.g., node 6 in Figure 5d) with node 32 (not shown) the least excited because of the damping effect due to the tank. Finally, for a given discharge, it should be noted that the most stressed part of the system is the one with the smallest pipe diameters (i.e., nodes 7—shown in Figures 5b and 8—not shown), and not the one in the close proximity of the end-user 7u (and then the service line). The reason of this important result will be explained in the following. In order to pinpoint the most excited part of the network in the successive phases of the transients, in Figure 6 the values of the hoop stress achieved at the end of the transient, σ_e, are evaluated for all the series. The analysis of this figure offers two comments, in line with the results already mentioned. First, in all the measurement sections, the extreme values of σ_e are achieved in series #2 and #3. Precisely, the smallest values are attained in series #2 (Figure 6b) because of the proximity of the transient generation point to the tank that damps the pressure waves. On the contrary, the largest values occur in series #3 (Figure 6c), since the generation point is located not only far away from the tank, but also in the portion of the network with the smaller diameter pipes. Second, in line with this remark, for all the test series, the most excited portion of the main network is the one with smaller diameter pipes (i.e., nodes 7 and

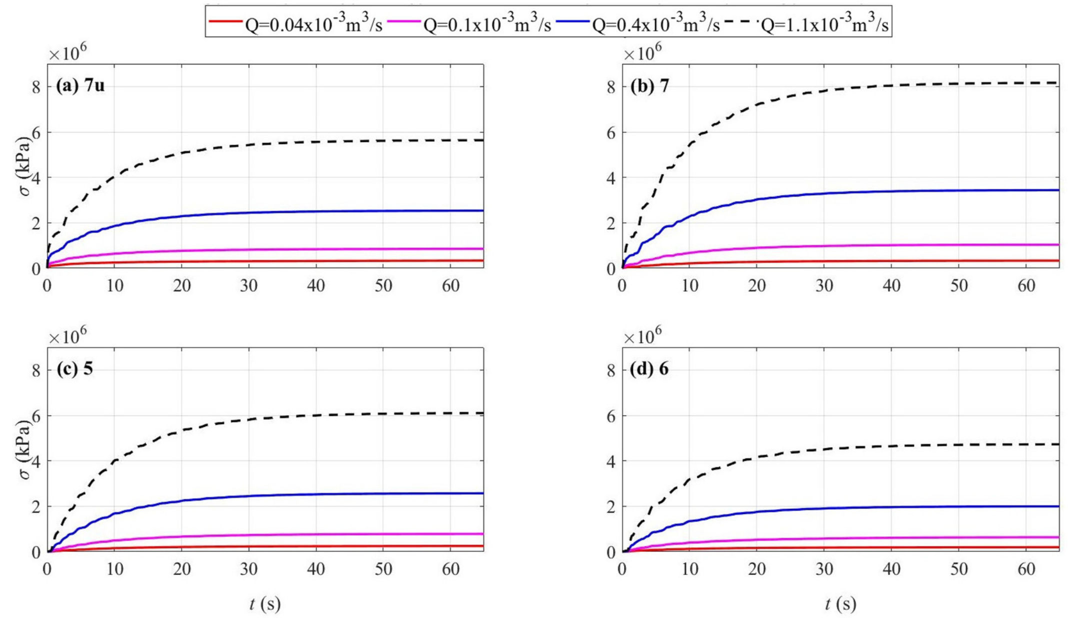


Figure 5. Test series #3—time-history of the cumulative hoop stress, σ, for $Q_{0,7u} = 0.04, 0.1, 0.4, 1.1 \times 10^{-3}$ m^3/s acquired at nodes: (a) 7u, (b) 7, (c) 5, and (d) 6.

8), regardless of where the transient is generated. This can be explained by the fact that larger amplitude pressure waves enter in such pipes but smaller amplitude ones exit. In other words, in a contraction, the transmitted wave is larger than the reflected one and the vice-versa happens in a enlargement. The so called "head accumulation"—already tested in Bohorquez et al. (2020) but in a single pipe (with a connection in series) for transients generated in the larger diameter pipe (low impedance)—happens also in a WDN for transients generated in the downstream end section of a service line.

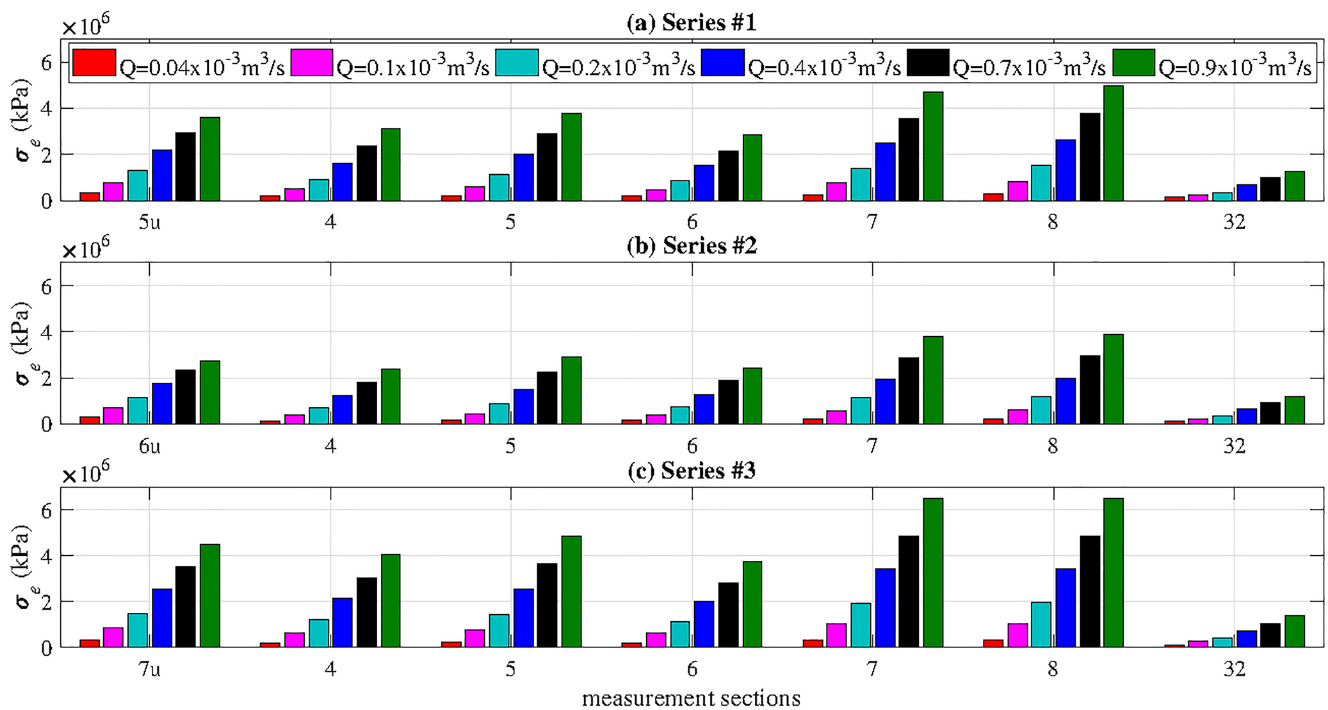


Figure 6. (a) Test series #1, (b) test series #2, and (c) test series #3—the end value of the cumulative hoop stress, σ_e, at the measurement sections for different discharge variations.

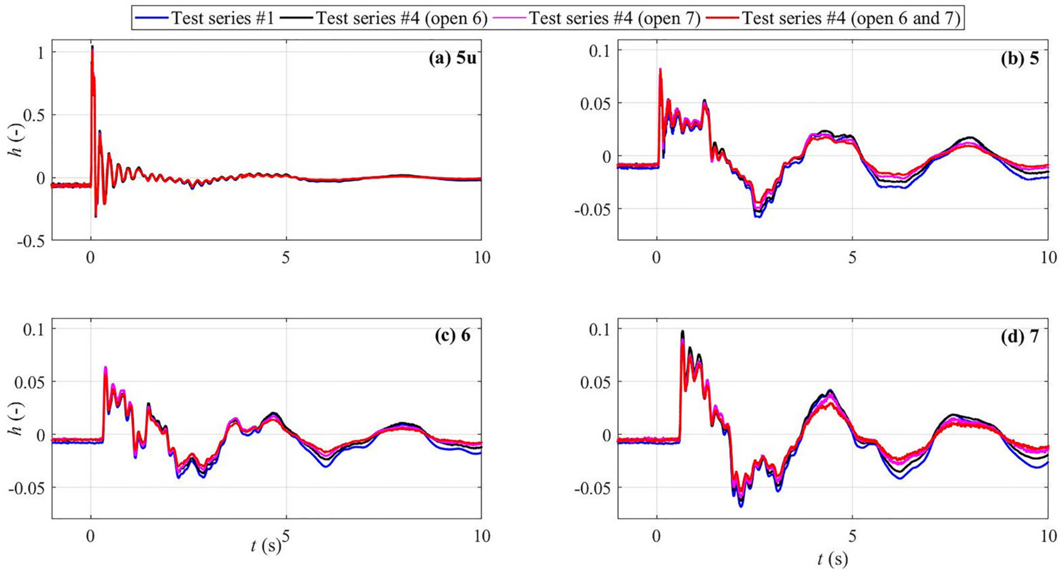


Figure 7. Test series #1 (with $Q_{0,5u} = 0.4 \times 10^{-3}$ m^3/s) versus test series #4—dimensionless pressure signal, h, at nodes: (a) 5u, (b) 5, (c) 6, and (d) 7.

6. Combined Effect of Simultaneous Consumers

6.1. Series #4: Effect of Deterministic Water Consumption Variations

In order to better understand the combined effect of further consumers, test series #4 of Table 1 has been carried out and compared with those of test series #1. In series #4, transients are generated by the fast and total closure of the end-user 5u, as for series #1, but with users still active at connections 6 or/and 7 (hereafter, referred to as users 6 or/and 7, for the sake of brevity). The dimensionless pressure signals are reported in Figure 7, for a given consumption variation, $Q_{0,5u}$ (= 0.4×10^{-3} m^3/s). The larger the consumption at the users 6 or/and 7, the smaller the pressure variations in all the measurement sections. In fact, total reflection does not occur at the active users that do not behave as a dead end, where pressure variations double. Moreover, for a given discharge, $Q_{0,6} = Q_{0,7}$ (= 0.3×10^{-3} m^3/s), the damping of the pressure waves is larger when the user 7 is active with respect to the case of the active user 6. This feature is justified by the already mentioned key role of the portion of the network with smaller diameter pipes, that amplifies the reflection of the pressure waves. Such a behavior is confirmed by the time-history of the hoop stress of tests of Figure 7, shown in Figure 8: the larger the total consumption through the users 6 or/and 7, the less stressed the network, as well as the service line. Moreover, it is clear that, for a given consumption, the location of the active user is crucial. In fact, the stress in the whole network is smaller when user 7 is active. Finally, even if the network is open, in any case the most excited part of the network still remains the one with the smaller diameters (as an example, node 7 in Figure 8d).

6.2. Series #5: Effect of Random Water Consumption Variations

In test series #5, the transient behavior of the laboratory DMA is checked considering 1 hr of random water consumption variations in all the three end-users (i.e., nodes 5u, 6u, and 7u), for a total of more than one hundred and fifty opening and closing maneuvers, according to the field monitoring of real users (Marsili et al., 2021, 2022). More specifically, the water consumption variations, imposed at the three end-users, are equivalent: each end-valve is set to generate a water consumption variation of 0.2×10^{-3} m^3/s, when all the other end-users are closed. Furthermore, the same pattern, but opportunely offset, is imposed at each end-user. The resulting cumulative hoop stress in all measurement sections is reported in Figure 9. Such a plot confirms that the most stressed part of the network is the one with the smallest diameter pipes (nodes 7 and 8): along time, such a part becomes more stressed than the service lines themselves (nodes 5u, 6u, and 7u).

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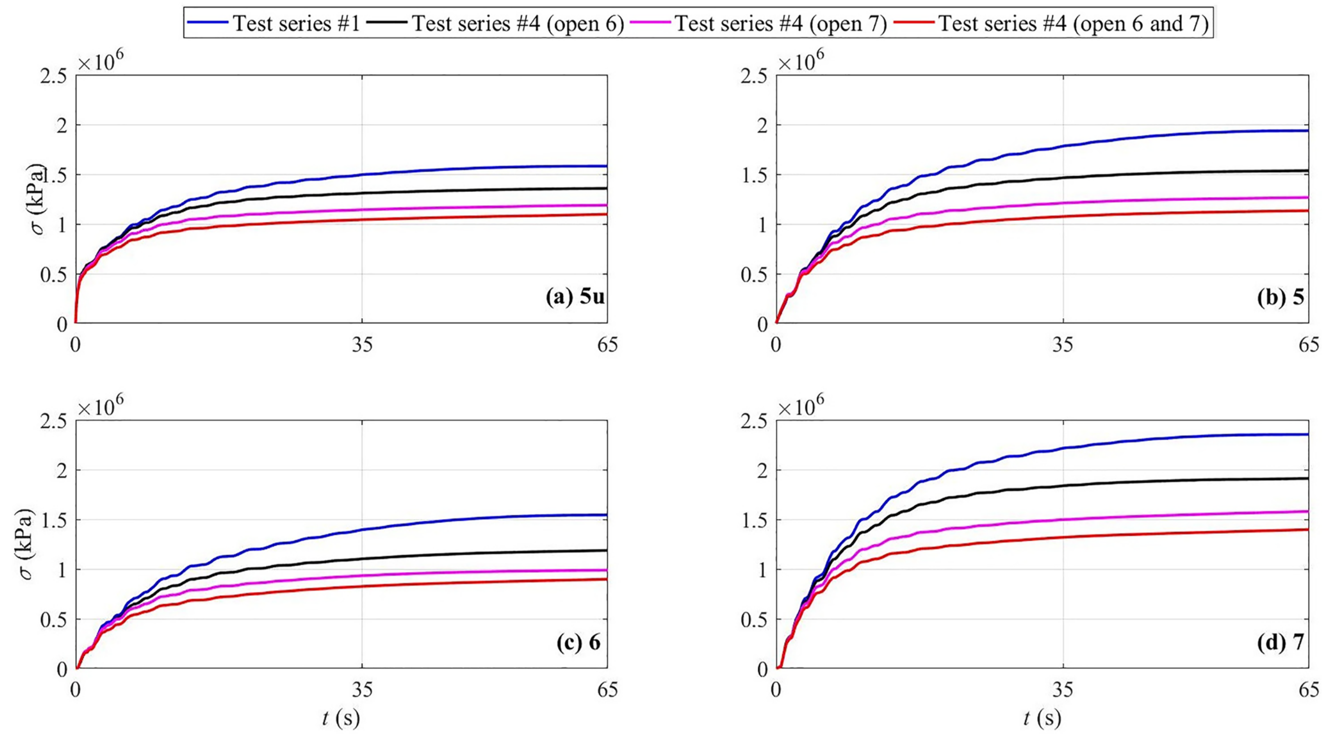

Figure 8. Time-history of the cumulative hoop stress, σ, at sections: (a) 5u, (b) 5, (c) 6, and (d) 7 for test series #1 (with $Q_{0,5u} = 0.4 \times 10^{-3}$ m^3/s) versus test series #4.

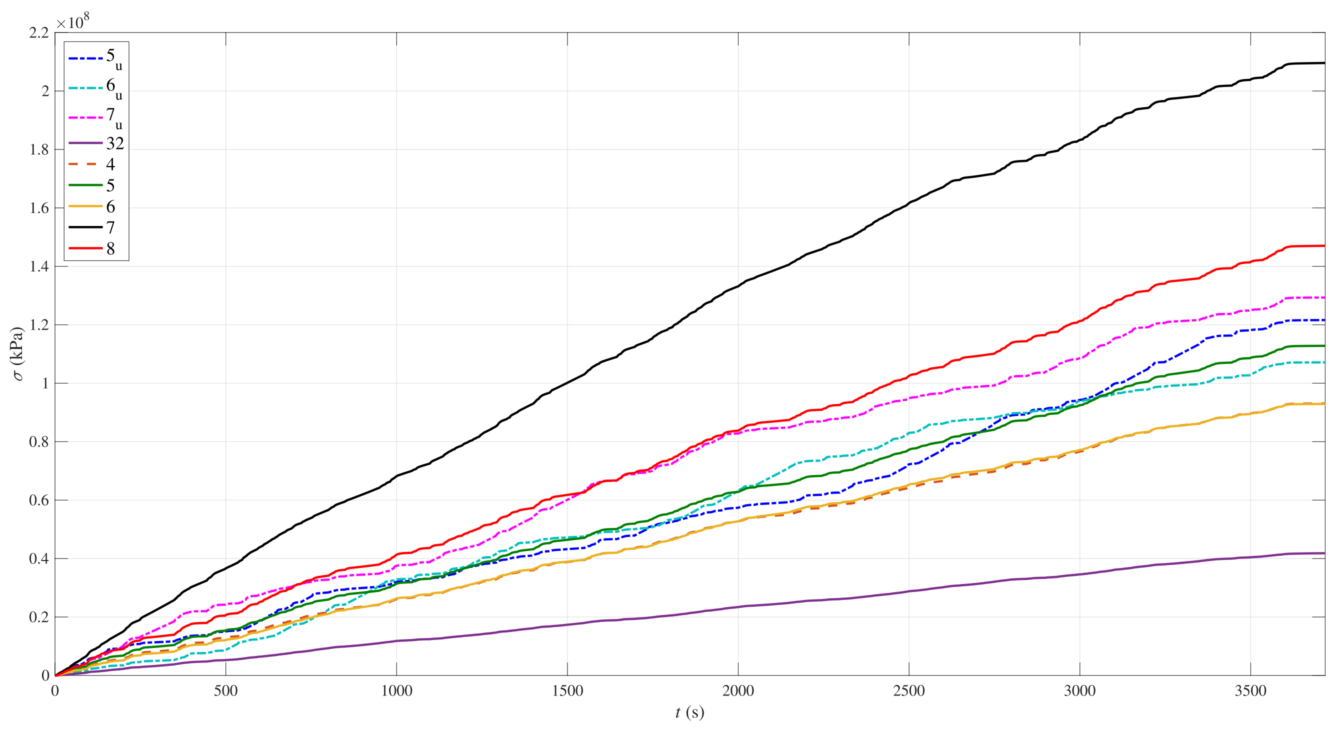

Figure 9. Test series #5: time-history of the cumulative hoop stress, σ, at all measurement sections.

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7. Conclusions

Transient tests have been carried out at the WEL of the University of Perugia, Italy—in a polymeric pipe network with two 100 × 100 m square loops, simulating a DMA—with the aim of analyzing the dynamic behavior of the system due to users' consumption changes. Closure maneuvers are carried out in the service lines, located in different nodes of the network, to generate controlled, repeatable, and fast transients. Such transients emphasize the dynamic response of the system and enable highlighting the mechanism of interaction of pressure waves with the network components.

Transients differ in the entity of the water consumption variation, location, and number of the active end-users.

The major findings of this study are as follows:

- the tests show that the service lines are overexcited and cavitation can occur particularly when the discharge in the service line is large (Figure 2);
- cavitation does not occur when the service connection differs less in diameter from the nearby pipes, as for junction 7 (Figure 3);
- the larger the water consumption at the end-users is, the larger the pressure variations (Figure 2), and the more stressed both the service line and the main pipes are (Figure 5);
- the most stressed part of the WDN is the one with the smaller diameters regardless of where the transient is generated when the water consumption varies both deterministically (Figure 6) and stochastically (Figure 9);
- the active end-users behave like pressure relief valves that dampen the transient events (Figure 7);
- for a given consumption, the largest transient pressure damping occurs when consumers are located in the part of the network with the smallest diameter pipes (Figure 7);
- the most severe transients occur when there are no further end-users consuming water beyond the one where the maneuver is carried out (Figure 8).

The lessons learnt from such findings may help the water utility managers to identify the possible reasons of the higher frequency of occurrence and severity of faults in some specific parts of WDNs apparently "similar" to other parts where damages are less frequent and severe. The first reason could be the occurrence of severe consumption change due to the activity of important users during the night when large parts of the network are almost inactive. The second reason could be the repetitive and fast maneuvers (not necessarily severe) especially when they are carried out in the night (see above). The third reason could be the percentage of small diameter pipes. Moreover, the higher the diameter gradient, with respect to the nearby pipe diameters, the larger the head accumulation (i.e., the progressive exaltation of the pressure waves). Such findings can help the water utility managers to better understand the WDN behavior in the view of its transient response: a larger number of leaks/faults is expected in areas with large consumers in the night or in the networks with regular fast maneuvers carried out in the night, in areas with the smallest diameters and a higher diameter gradient with respect to the nearby pipe diameters.

The main aim of the future research is to make the laboratory set-up at WEL, the closer and closer to real WDNs. The first upgrade option is to install a device (a PRV or a variable speed pump) to check its role during transients due to change of water consumption. Successively, the transient response of service lines to maneuvers carried out in the main pipes (e.g., pump trip) could be explored. Moreover, the complexity of the network could be enhanced by increasing the number of loops, and pipe materials. Last but not least, different types of anomaly (e.g., leaks with a fixed area, slits (Ferrante et al., 2013), as well as cracks) and constraints (Covas et al., 2004) could be included.

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Data Availability Statement

Data are available at the following link: https://doi.org/10.5281/zenodo.5535441.

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